REMARKS

Claims 22-24, 29-30, 32 and 36 are pending. Claims 1-21, 25-28, 31 and 33-35 are canceled. Claim 36 is amended.

Claims 22-24, 29-30, 32 and 36 stand rejected under 35 U.S.C. §103(a) as being unpatentable over Takahashi (US Patent No. 4,388,098) in view of Tikkanen (Finnish Patent No. 98832) and Ainsle (US Patent No. 4,923,279). Applicants respectfully request reconsideration and withdrawal of the rejection.

The Claimed Process

Claim 36, the sole independent claim pending in the application, reads as follows:

> A method for forming multicomponent glass particles and spraying the particles to a target, the method comprising:
>
> supplying a fuel gas through a nozzle of a spraying device to produce a flame;
>
> introducing oxygen to the flame through the nozzle;
>
> introducing a first glass component to the flame through the nozzle such that the first glass component reacts to form first oxide particles, wherein the first glass component is a gaseous or vaporous substance;
>
> introducing a second glass component to a vicinity of the flame through the nozzle, wherein the second glass component comprises a liquid solution containing a rare earth metal;
>
> introducing an atomizing gas to the vicinity of the flame through the nozzle;
>
> atomizing the second glass component with the atomizing gas in the vicinity of the flame so as to form second oxide particles; and
>
> causing the first oxide particles and the second oxide particles to combine with each other so as to form multicomponent glass particles comprising the rare earth metal.

As shown above, claim 36 is amended to improve clarity, by reciting introducing the second glass component to a vicinity of the flame *through the nozzle*, and reciting the formation of multicomponent glass particles *comprising the rare earth metal*. Support for these amendments is found, for example, in the paragraph beginning on line 34 of specification page 5, in Figures 1-2 and on specification page 5, lines 6-12.

The claimed multicomponent glass particles are formed of a first glass component and a second glass component which comprises a liquid solution containing a rare earth metal. The multicomponent glass particles are formed in such a manner that the second glass component forms dopant particles into a glass matrix. When the inventors developed the claimed method, they noticed that the first glass component tended to react more slowly with oxygen than rare earth metals react with oxygen. Thus, the dopant particles accumulated into the core of the multicomponent glass particles, and silicone dioxide particles placed themselves on the dopant particles. When the dopant particles were very close to each other, the started to interact, which resulted in poor efficiency of amplification. In order to produce more homogeneous particles, the inventors discovered that it was necessary to atomize the liquid dopant component in the vicinity of the flame of a spraying device. The reaction in the flame is quick, and therefore prevents sequential deposits of different components.

The claimed process provides improved homogeneity of the multicomponent glass particles. This leads to improved amplification properties in the active fibers and enables tailored structures to be made. The improved homogeneity of the resultant glass particles of the claimed process is demonstrated in the photographs presented in the attached Appendix, which show a preform made by the claimed process and a preform made by a modified chemical vapor deposition (MCVD) process. It is clear from the photographs that the claimed process yields more homogeneous glass particles.

Additionally, the claimed process is economically advantageous. For example, when compared to a MCVD process, the claimed process obtains a much better yield, because the claimed process rarely generates defects. In a MCVD process, the yield per layer is every fifth

preform; due to the fact that many layers are required to be formed on top of each other, the total yield is fractional.

Applicant encloses, in the attached Appendix, the article *Direct Nanoparticle Deposition Process for manufacturing very short high gain Er-doped silica glass fibers* (S. Tammela, P. Kiiveri, S. Sarkilahti, M. Hotoleanu, H. Valkonen, M. Rajala, J. Kurki and K. Janka, ECOC 2002 Proceedings, Volume 4, 9.4.2, September 2002). This article provides evidence of the beneficial effects of the claimed process. For example, please see Figures 2 and 3. Applicant also encloses herewith the article *Potential of nanoparticle technologies for next generation rare earth doped fibers* (S. Tammela, M. Hotoleanu, K. Janka, P. Kiiveri, M. Rajala, A. Salomaa, H. Valkonen and P. Stenius, invited paper, OFC:04 Technical Digest, February 22-27, 2004. This article also presents evidence of benefits of the invention. Additionally, Applicant includes the article *Potential of nanoparticle technologies for next generation erbium-doped fibers* (S. Tammela, M. Hotoleanu, K. Janka, P. Kiiveri, M. Rajala, A. Salomaa, H. Valkonen and P. Stenius, Liekki Oy, Sorronrinne 9, FI-08500 Lohja Finland) as further evidence of the benefits of the invention.

The Applied Prior Art

Takahashi discloses a method in which a liquid component is nebulized in a separate nebulizer (indicated by reference numeral 13 in Fig. 1) by supersonic vibration, or by carrier gas supplied from a conduit (indicated by reference numeral 24a in Fig. 2). As can be seen in Figs. 1 and 2 of Takahashi, the nebulized dopant solution is exposed to ambient air before the controlled reaction in the flame takes place. Therefore, if rare earth metals were used in the dopant solution, as claimed in present claim 36, the rare earth metals would begin to oxidize before reaching the flame and would form a clustered structure. Furthermore, it is very possible that the droplets of nebulized solution would tend to accumulate into larger drops due to the delay in reaching the flame, thereby exacerbating the clustering of the sprayed particles.

Tikkanen discloses a method in which a liquid component is atomized into droplets in the immediate vicinity of a flame in order to produce small particles. Tikkanen does not teach or even suggest the use of rare earth metals or multicomponent glass particles.

The Examiner has taken the position that the method disclosed by Takahashi can be altered such that the nebulizing process in Takahashi is replaced with the atomizing process of Tikkanen. However, there is no motivation to modify Takahashi as suggested by the Examiner. Takahashi does not provide any suggestion of the desirability of the claimed process, and Tikkanen does not provide any suggestion why one should atomize components in the vicinity of a flame in order to produce multicomponent glass particles. In fact, when the Tikkanen disclosure is viewed in its entirety, it teaches away from the claimed process by presenting, in a discussion of prior art, that it is not proper to simultaneously produce and dope glass. See MPEP Section 2141.02, which states that prior art must be considered in its entirety, including disclosures that teach away from the claims. Distilling an invention down to the "gist" or the "thrust" of the invention disregards the requirement of analyzing the subject matter "as a whole." *W.L. Gore & Associates, Inc. v. Garlock, Inc.*, 721 F.2d 1540, 220 USPQ 303 (Fed. Cir. 19830, cert. denied, 469 U.S. 851 (1984).

Contrary to the claimed simultaneous process, Tikkanen suggests that the dopant can be sprayed on the surface of the glass material in such a manner that small particles infiltrate into the glass material, thus coloring the glass material. Tikkanen does not suggest in any way that multicomponent glass particles could result from the disclosed process because there are no precursors present for multicomponent glass particles (the cobalt ions only form small cobalt oxide particles which penetrate into a desired object). Furthermore, whereas the object of the claimed process is to produce light intensifying characteristics, Tikkanen is instead directed to coloring an object.

The Examiner has also taken the position that the teachings of Ainslie would motivate one to supply a rare earth metal in the Takahashi method. As stated above, there is no motivation to modify Takahashi's teachings so as to supply a rare earth metal to the Takahashi method. Ainslie does teach a method using a rare earth metal. However, the method of Ainslie is completely different from the claimed method and the methods described in Takahashi and Tikkanen. Ainslie teaches using a rare earth metal solution in an immersion process rather than a

spraying process, and the solution is used alone, rather than simultaneously with other precursors of glass material.

Based on the discussion above, it is clear that, even if the references are combined as suggested by the Examiner, the combination would not result in the claimed invention. Furthermore, none of the references cited by the Examiner disclose the homogeneity problem addressed by the claimed invention, and there is no motivation to combine the references as suggested. When the cited prior art is viewed as a whole, the prior art does not teach or even suggest the claimed process.

Conclusion

In view of the above amendment, applicant believes the pending application is in condition for allowance.

Applicant believes no fee is due with this response. However, if a fee is due, please charge our Deposit Account No. 22-0185, under Order No. 20386-00294-US from which the undersigned is authorized to draw.

Dated: February 4, 2005

Respectfully submitted,

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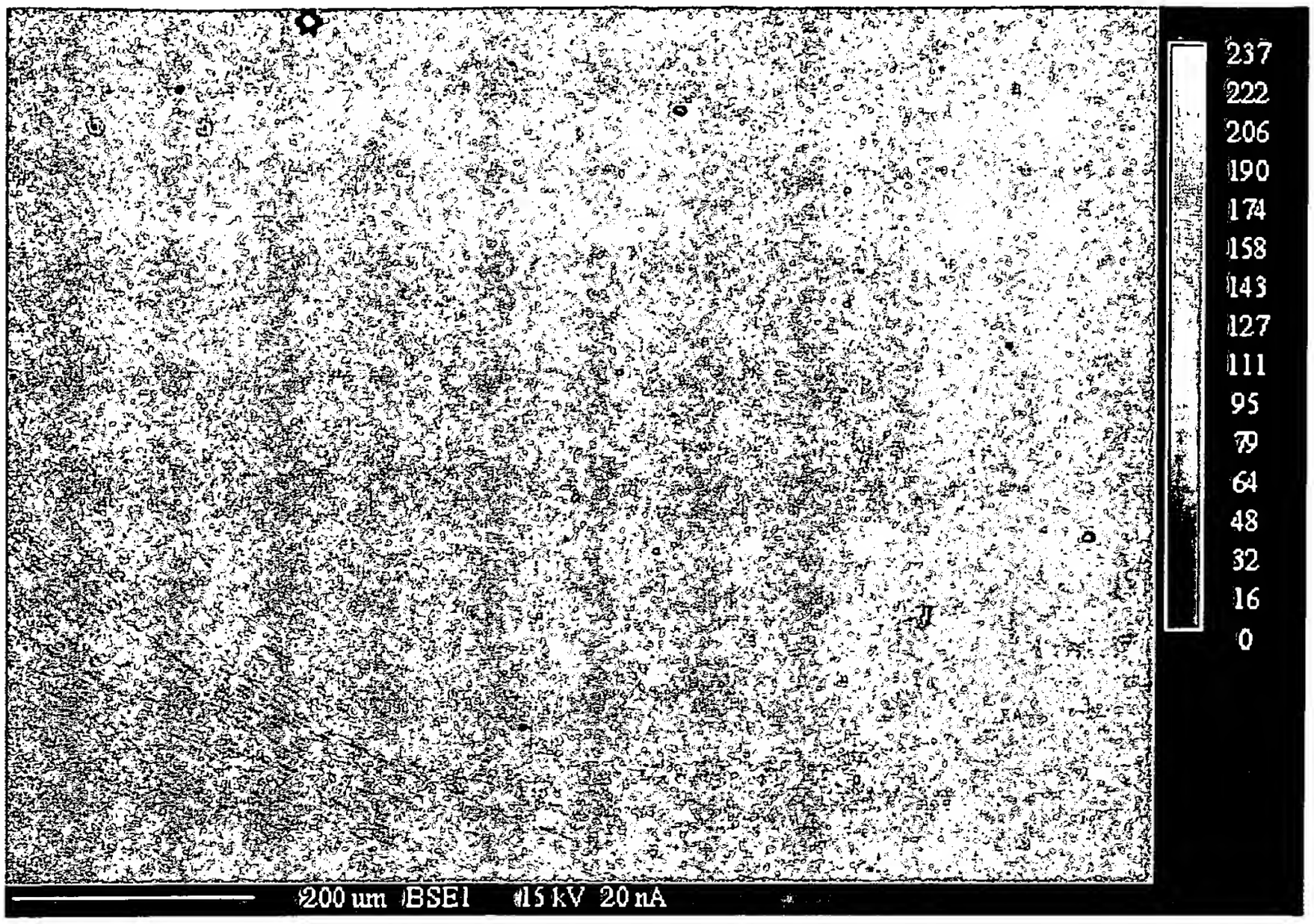
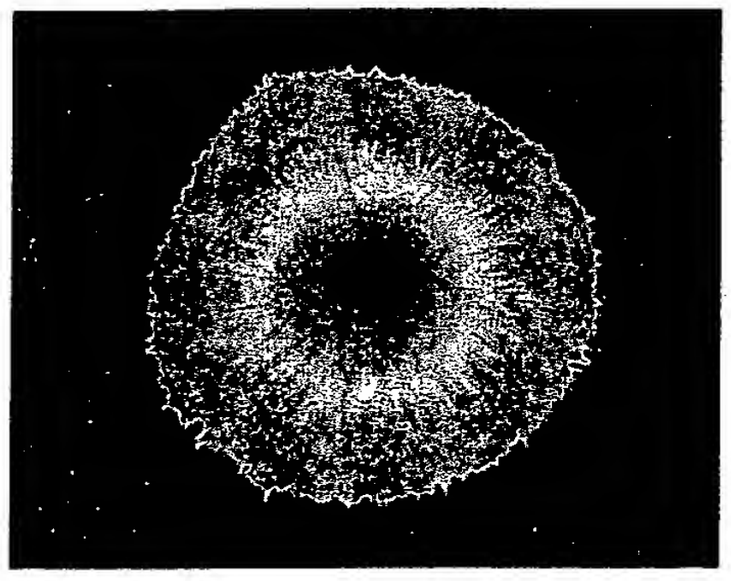


Preform According to Invention



Preform from MCVD Process

Direct Nanoparticle Deposition process for manufacturing very short high gain Er-doped silica glass fibers

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Abstract *The new Direct Nonoparticle Deposition process yields fibers with very high Erbium concentrations and flat gain characteristics. A gain of 38dB has been obtained from 1.2m of silica based Er-doped fiber with 110mW pump power.*

Introduction

The need for low cost, high performance WDM based optical networks is increasing because of the vastly expanding bandwidth demand from broadband access systems. The growing number of amplifiers needed in WDM based optical networks make Erbium doped fiber amplifiers critical elements. In very high bit-rate systems reducing the length of the amplifying fiber is important to minimize problems due to non-linear effects, and polarisation mode dispersion.

Our aim has been to develop a process that gives high and flat gain profile in a short length of fiber, and therefore results in better economy for Metro WDM applications and improved performance for very high bit-rate systems. The further target has been to develop a deposition technology that is suitable for manufacturing of other doped fibers, such as Neodymium doped fibers for lasers and for manufacturing of high gain planar waveguide amplifiers.

Optical fibers have been usually fabricated by flame hydrolysis or chemical vapour deposition (CVD) processes. Both methods use gases or high vapour pressure liquids as precursors. Adding rare earth elements and certain co-dopants in the glass is difficult since there are not stable volatile high vapour pressure precursors for those materials. The rare earth elements and co-dopants have been usually added to the core by a solution doping method that comprises four phases [1]. The solution doping process relies on diffusion of the elements, which makes it difficult to control the rare earth doping level and homogeneity of the refractive index profile.

Generally the doping of rear-earth metals to silica-based glass material has two major problems. First, the vapour pressures of useful compounds are too low for CVD or flame-hydrolysis processes. The second general disadvantage is that the glass synthesis or doping processes are usually rather slow, so that Erbium ions have enough time to cluster (or form pairs).

In this paper a new Direct Nanoparticle Deposition (DND) process is introduced and the results obtained using very high Erbium concentration in short fibers are presented.

DND process and fiber manufacturing

The new Direct Nanoparticle Deposition process overcomes the problems mentioned above. Feeding the precursor solution in liquid phase directly to the reaction zone overcomes the usual Erbium-concentration limit, which is typical to the other processes. In this process the glass is doped in-situ with the glass particle formation in such a way that the clustering tendency is low. Thus the DND process makes it possible to mix the index difference forming materials with other dopant materials already during the deposition of the glass particles which improves the homogeneity of the glass composition prior to the

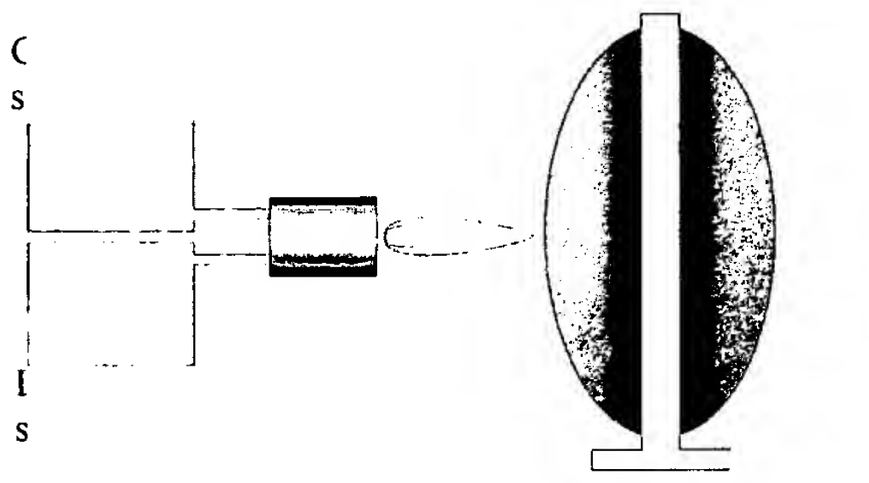

Fig. 1. DND process equipment

sintering phase. The DND process is depicted in Figure 1. The deposition is a special form of an outside soot deposition process where nanosize particles of dopants are inserted to the target simultaneously with silica deposition. The next phase is the sintering process that yields solid glass preforms.

The deposition process is automated and widely scalable. This new process allows accurate control of the radial index difference and dopant profiles in the fiber core. Furthermore, very high dopant concentrations with homogeneous glass structure are obtained.

Fiber measurements and results

Using the DND process we have produced pure Er/Al doped fibers with different erbium concentrations. The erbium concentration in fibers was increased from the normal values to very high values to test how it affects the gain properties of the fibers.

We present here the properties of a fiber containing 2200ppm of Er^{3+} ions in purely Al-codoped SiO_2. This caused 58dB/m peak absorption at 1530nm. Figure 2 shows a SEM picture of the preform end of that fiber. Smooth and accurate core cladding interface and circular geometry are observed. The aluminium and erbium dopant concentrations were measured using the electron probe microanalysis (EPMA). Radially homogenous, flat Er and Al concentrations were obtained (Figure 3).

Fig. 2. A SEM picture of the DND preform end. The circular area is the Al-codoped core

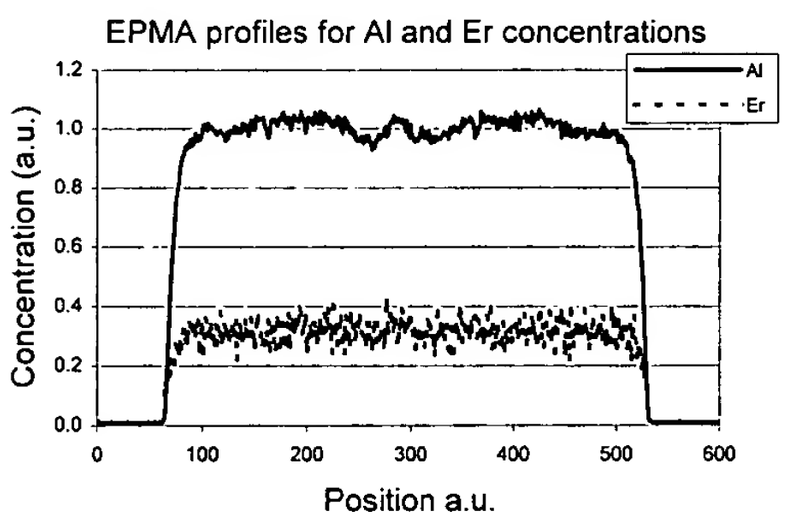

***Fig. 3*: Radial erbium and aluminium profiles in the core of the DND preform. The Er-profile is multiplied by 10 compared to the Al-profile**

The high Al-concentration allows to increase the Er concentration and the fully doped core area allows to increase the Er amount per length unit and still have a quantum conversion efficiency (QCE) of about 40%.

The spectral absorption of the fiber having a peak of 58dB/m is seen in Figure 4.

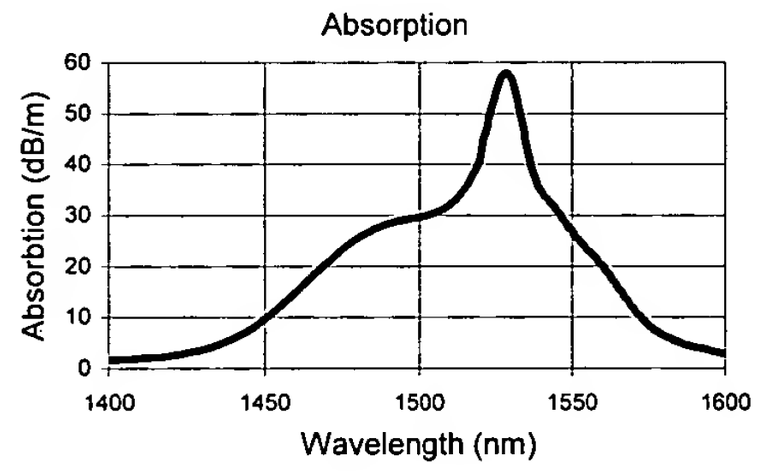

***Fig. 4*. Spectral absorption of highly doped Er-fiber. Absorption at 1530 nm is 57.8 dB/m**

The amplifying properties of the fiber with varying lengths from 1.2m to 1.5m are shown in Figure 5. A gain of 38dB is achieved with input power of -35dBm at 1530nm signal wavelength. The fiber was pumped with a 980nm laser using 110mW pump power. The good gain flatness is due to high aluminium concentration (5.7 mole %) that is easily accomplished by the DND process.

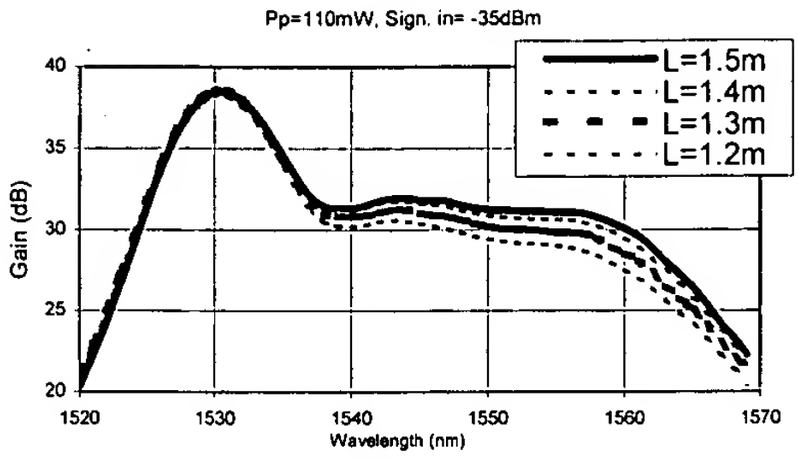

Fig. 5. Spectral gain curve showing flat gain at 1550 window for the high erbium fiber. Maximum gain with this setup at 1530 nm is over 38 dB

For 80cm fiber and 70mW pump power we have measured 28dB gain and 3.9dB noise figure at 1530nm and 21dB gain and 3.8dB noise figure at 1550nm.

We have tested the DND process for even higher Er concentrations. For peak absorption of 112dB/m the fiber still has QCE of 29.6% (fiber length 40cm, input signal 4dBm @ 1550nm, 90mW pump power). This QCE is better then the best results reported by 1999 for heavily doped fibers [2], [3], [4].

Conclusions

To verify the capabilities of the Direct Nanoparticle Deposition (DND) manufacturing process an Al/Si fiber having 2200ppm of Er^{3+} was made. The high Er concentration produced 38dB gain with 1.2m fiber and due to the pure alumina silica host the gain flatness was excellent. The Direct Nanoparticle Deposition (DND) manufacturing process allows very high and even erbium concentration to be deposited and also offers very good flexibility for various dopants. Due to the layered deposition process, the index profile and dopant concentration can be tailored to many applications including high gain optical fiber amplifiers and fiber lasers. Due to short fiber lengths needed, this fiber suits very well to 10-40Gb/s applications since non-linear effects and polarisation mode dispersion are minimized. The process has been industrialized and it offers excellent possibilities for manufacturing Erbium doped fibers for low cost Metro WDM applications.

References

1 P. Kiiveri, S. Tammela, Design and fabrication of erbium-doped fibers for optical amplifiers, Optical Engineering vol. 39, no.7, 1943-1950, 2000

2. P. Myslinski, D. Nguyen, J. Chrostowski, Effects of concentration on the performance of erbium-doped fiber amplifiers, Journal of Lightwave Technology, vol. 15, no. 1, 112-120, 1997.

3. P. Myslinski, C. Szubert, A.J. Bruce, D.J. DiGiovanni, B. Palsdottir, Performance of high-concentration erbium-doped fiber amplifiers, IEEE Photonics Technology Letters , vol. 11 no. 8, 973-975 1999.

4. M.R.X, de Barros, G. Nykolak, D.J. DiGiovanni, A. Bruce, W.H. Grodkiewicz, P.C. Becker, Performance of a high concentration Er/sup 3+/-doped alumino silicate fiber amplifier, IEEE Photonics Technology Letters , vol. 8 no. 6, 1996.

Potential of nanoparticle technologies for next generation rare earth doped fibers

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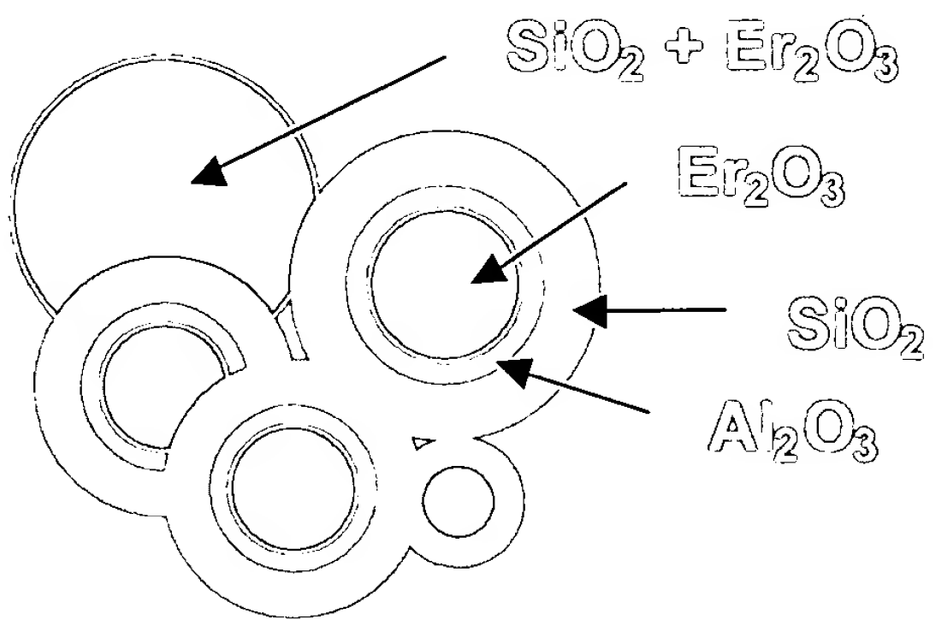
Content

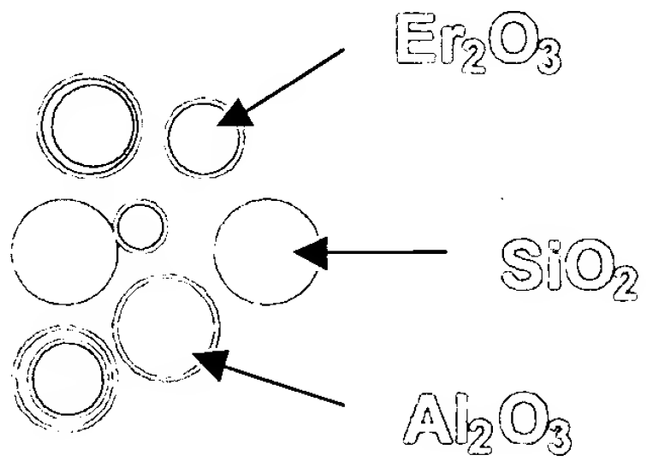
- Motivation
- What nanoparticle technology provides
- Direct Nanoparticle Deposition (DND)
- Properties of the DND glass
- DND fibers: properties
- Conclusions

Motivation for the search on new aproach

OVD / VAD
- laborous doping during soot deposition
- flame hydrolysis =>large particles



MCVD
- doping after soot deposition
- oxidation => small particles



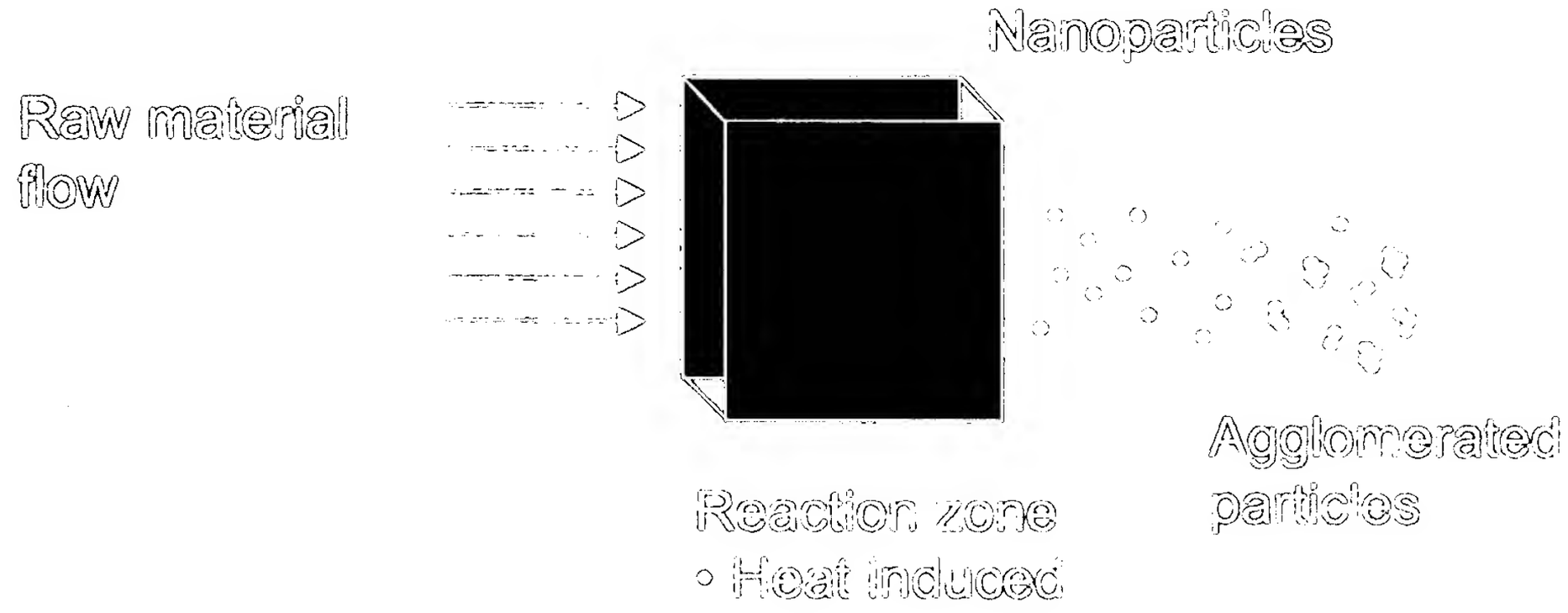
Reference "Optical Amplifiers: materials, devices, and applications", Shoichi Sudo editor, Artech House 1997

What nanoparticle technology provides

- Possibility to use high and low vapor pressure raw materials
- Good homogeneity of the sintered glass
- Homogeneous sites for the rare-earth ions

Some drawbacks

- Agglomeration limits the nanoparticle generation speed
- Small particle size results moderate growth rate



What nanoparticle technology provides

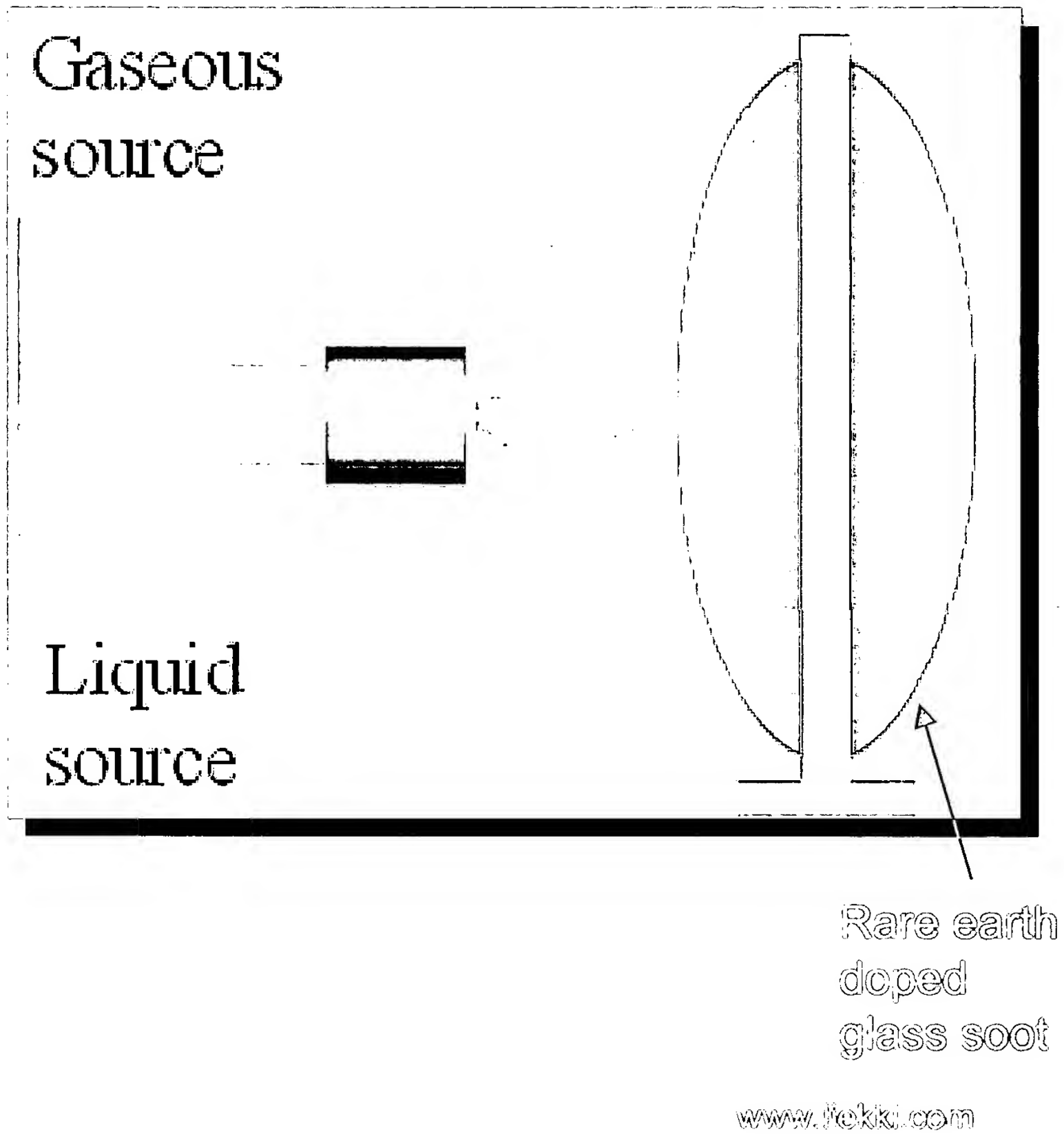
Nanoparticle process	Growth glass	Benefits in fiber
Precise control of the nanoparticle growth process	Homogeneous doping of active elements	Higher doping possible ◦ Shorter fiber required per application ◦ Lower cost ◦ Better performance on ◦ Bending loss, PMD and nonlinear effects
	Large variations of doped glass composition	Simpler glass structure ◦ Uniform local environment for the rare earth ions ◦ Repeatable spectral properties
	Accurate and independent control of doping concentration profile	Homogeneity and control on refractive index ◦ Less mode coupling in LMA fibers
	Better preform consistency	Short and large diameter core preform ◦ Simpler glass work ◦ LMA fibers with small core/cladding ratio
External deposition	Preform geometry is a flexible parameter	

Direct Nanoparticle Deposition (DND)

Liekki has developed a disruptive, propriety nanoparticle generation and deposition process

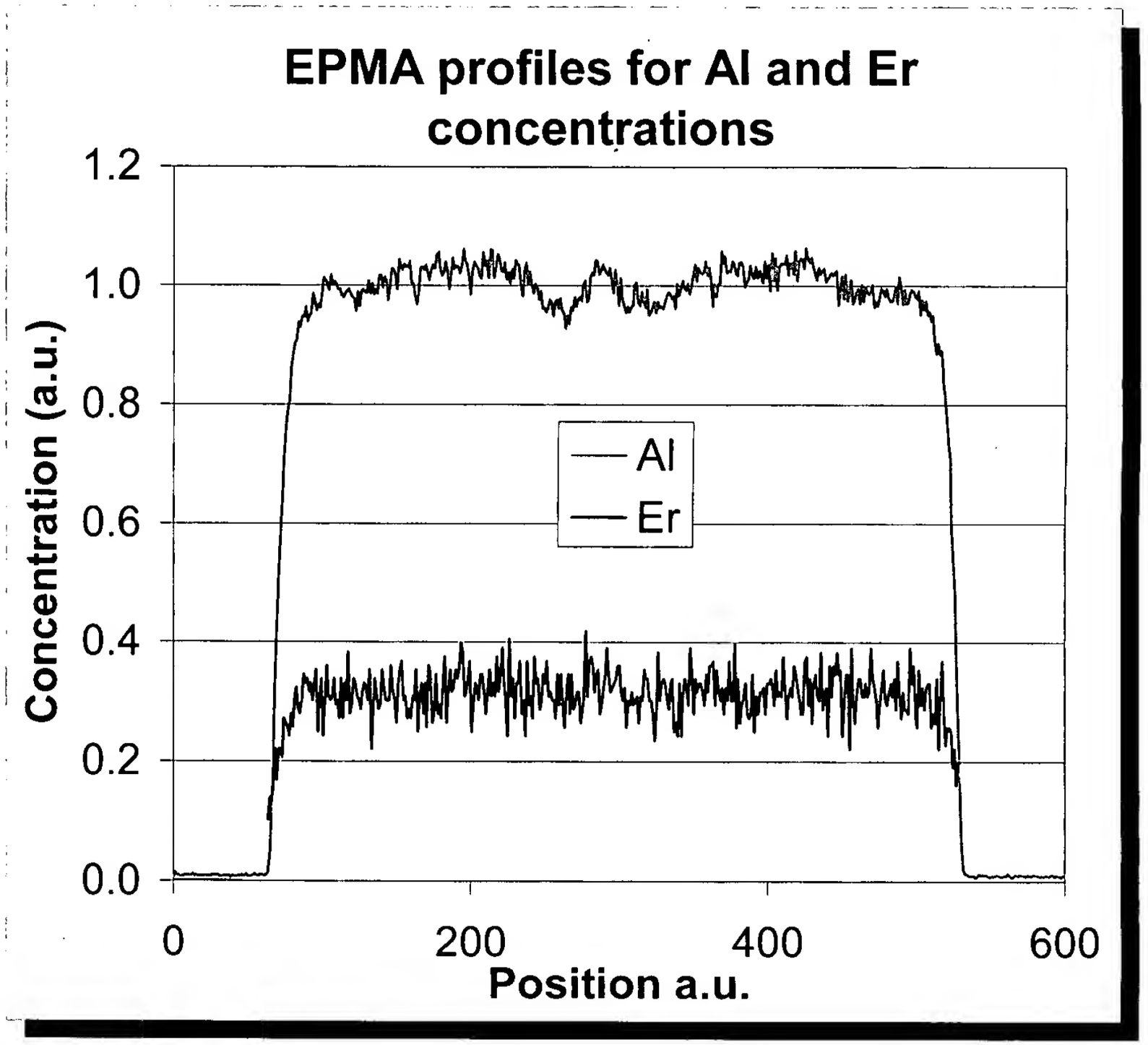
DND process

- Combustion of gaseous and atomized liquid raw materials
- Deposition immediately after particle generation



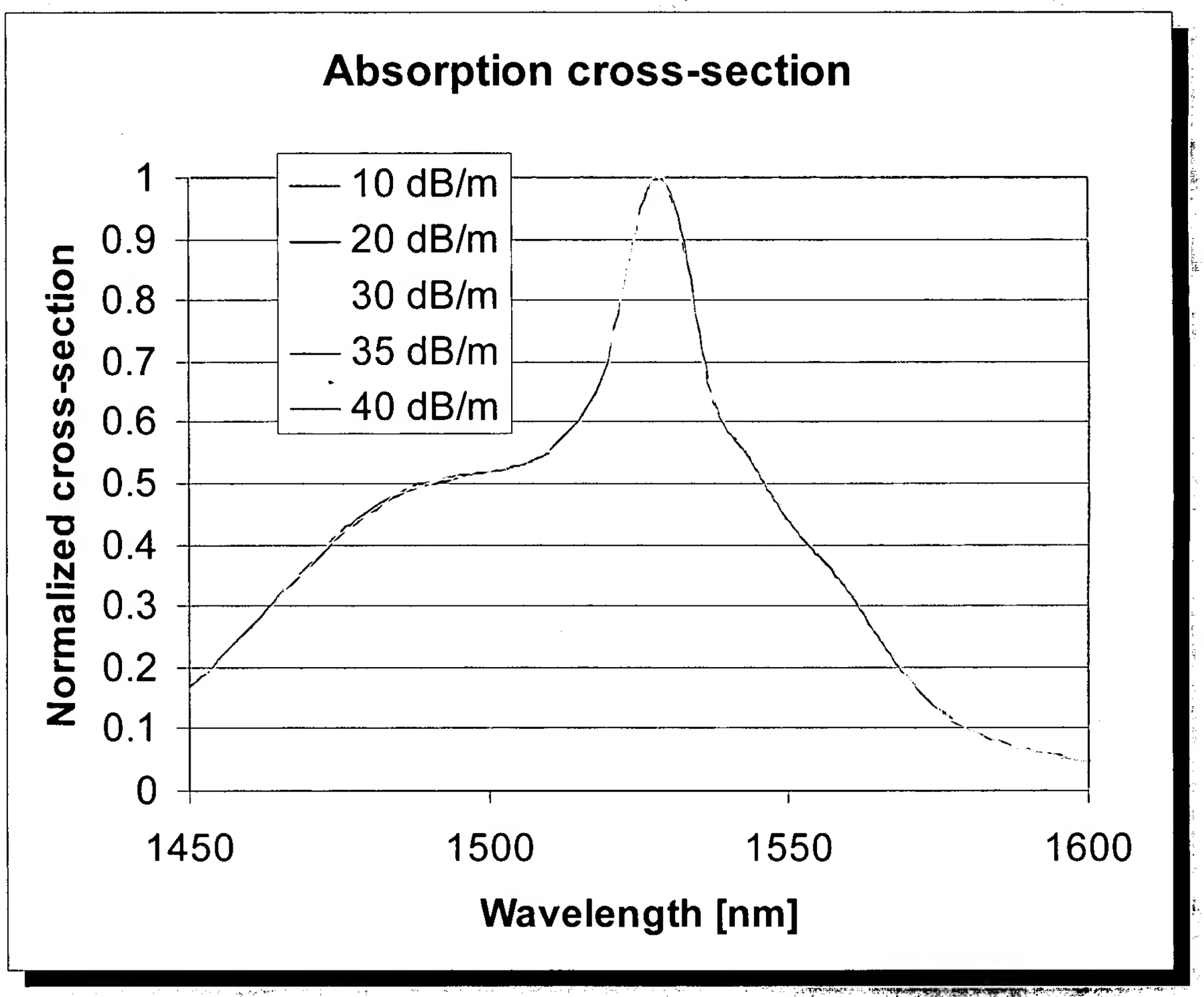
DND: doping uniformity in preform

- Core consists of about 100 layers
- The concentration variation within +- 5%
  - Temperature non-uniformity in the reaction volume
  - Process controlling at process start



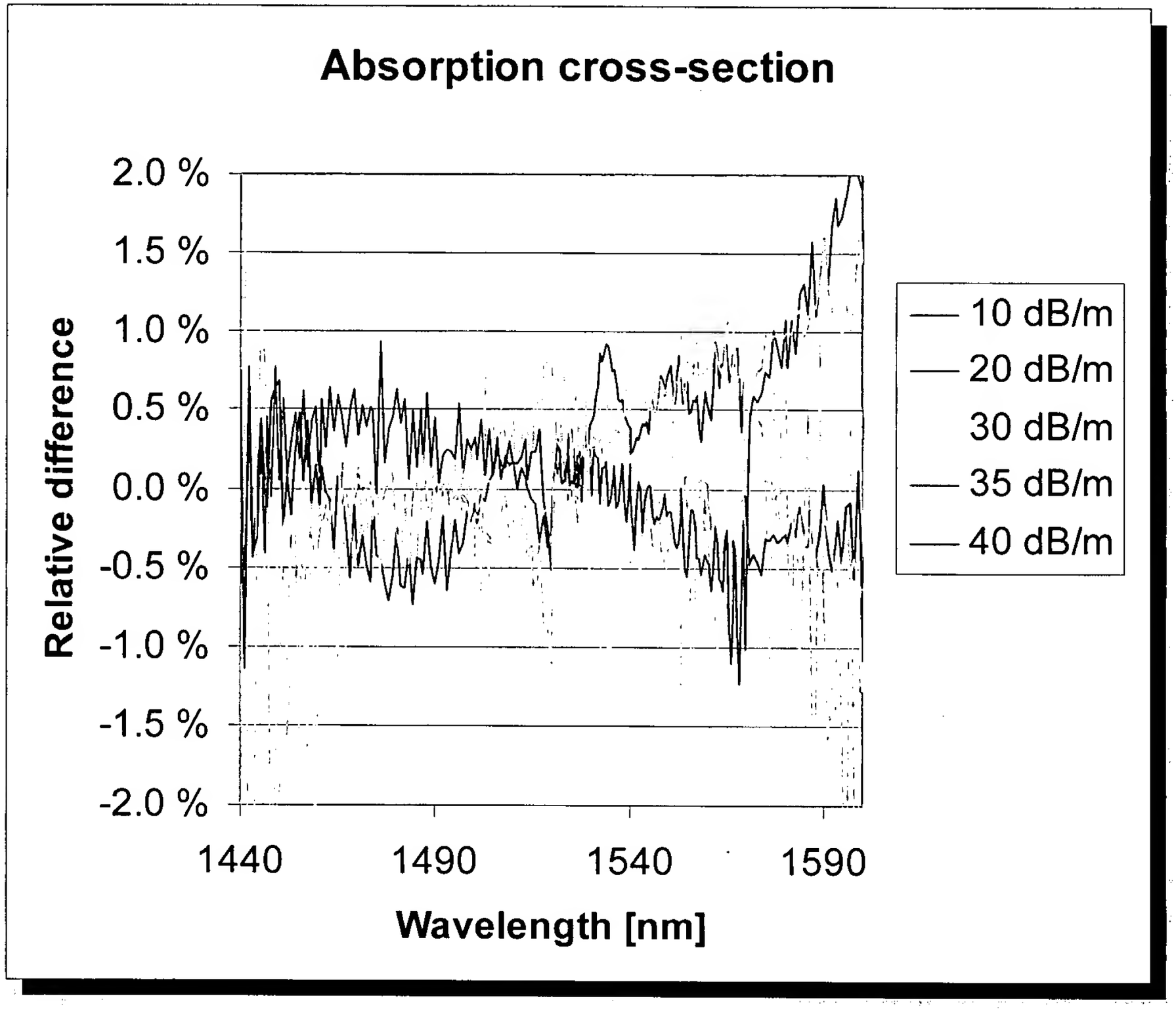
DND: Rare-earth local environment

- The cross-section is calculated from fiber absorption measurement
  - In the cross-section calculus the different cut-off wavelengths of the fiber is taken account



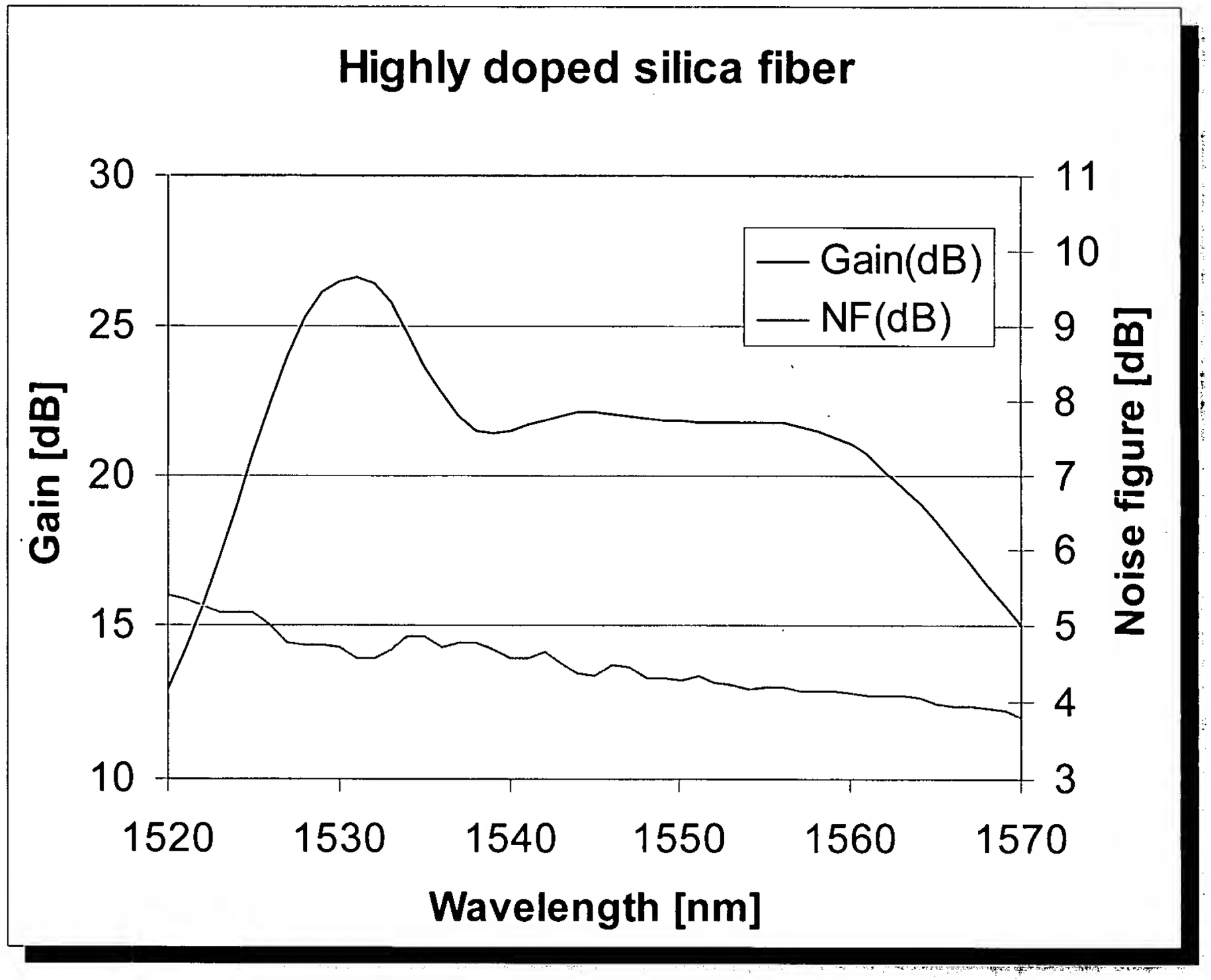
DND: Rare-earth local environment

- The differences on absorption cross-sections result mainly from in-accuracies in fiber coupling loss and cut-off variation
- The local environment for the rare-earth can be corsidered similar



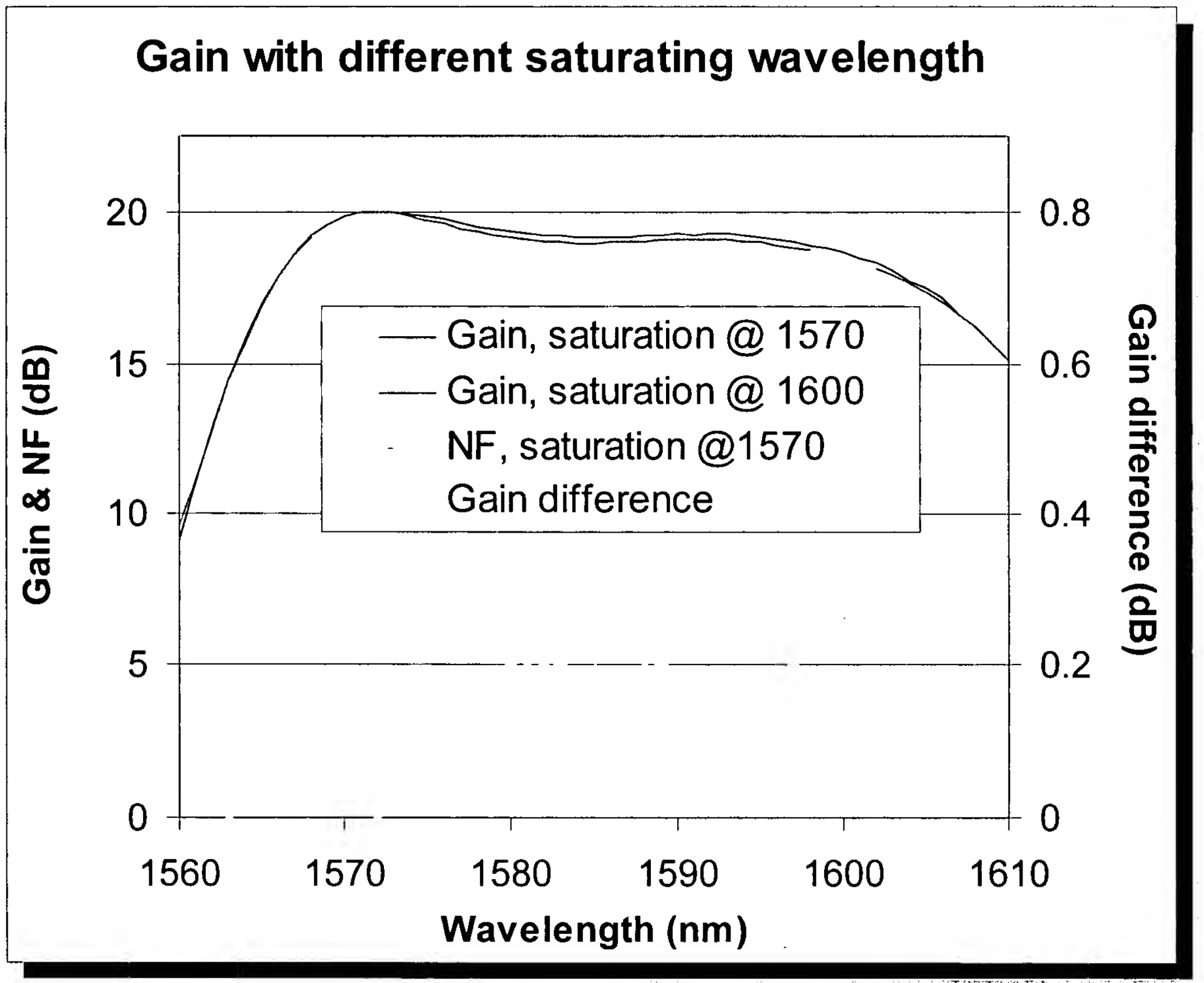
DND fibers: very short C-band fiber

- Uniform doping enables high doping with moderate up-conversion
- Absorption 100 dB/m @ 1530 nm
- Fiber length 0.58 m
- Pump 110 mW @ 980 nm
- QCE 21 % @ 0dBm input



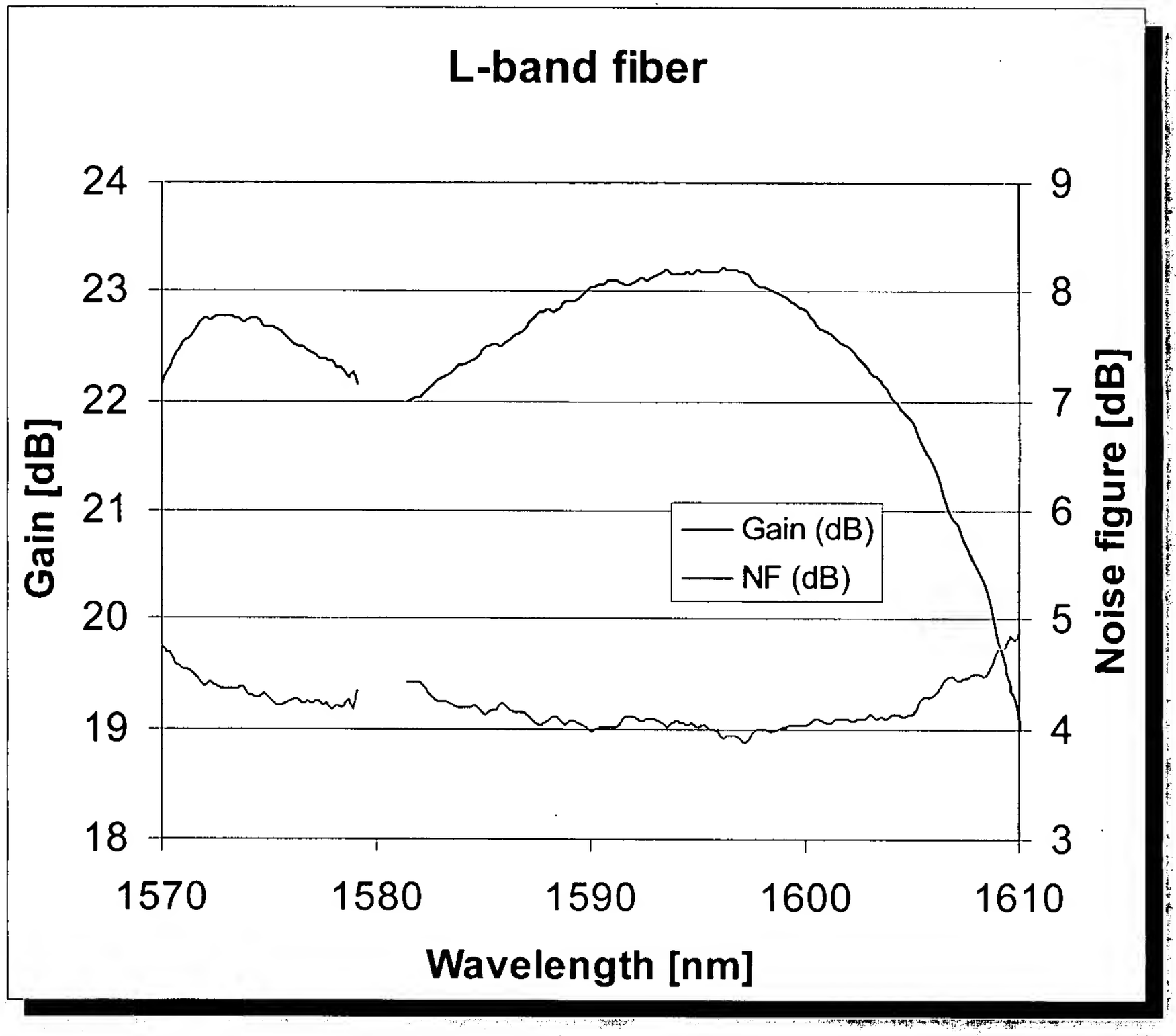
DND fibers: L-band fiber

- Small spectral hole burning
- Fiber Length=13.3m
- Saturating power 0 dBm
- Pump power: forward 100mW @977.5nm, backward 135mW @1475nm
- QCE 45 %



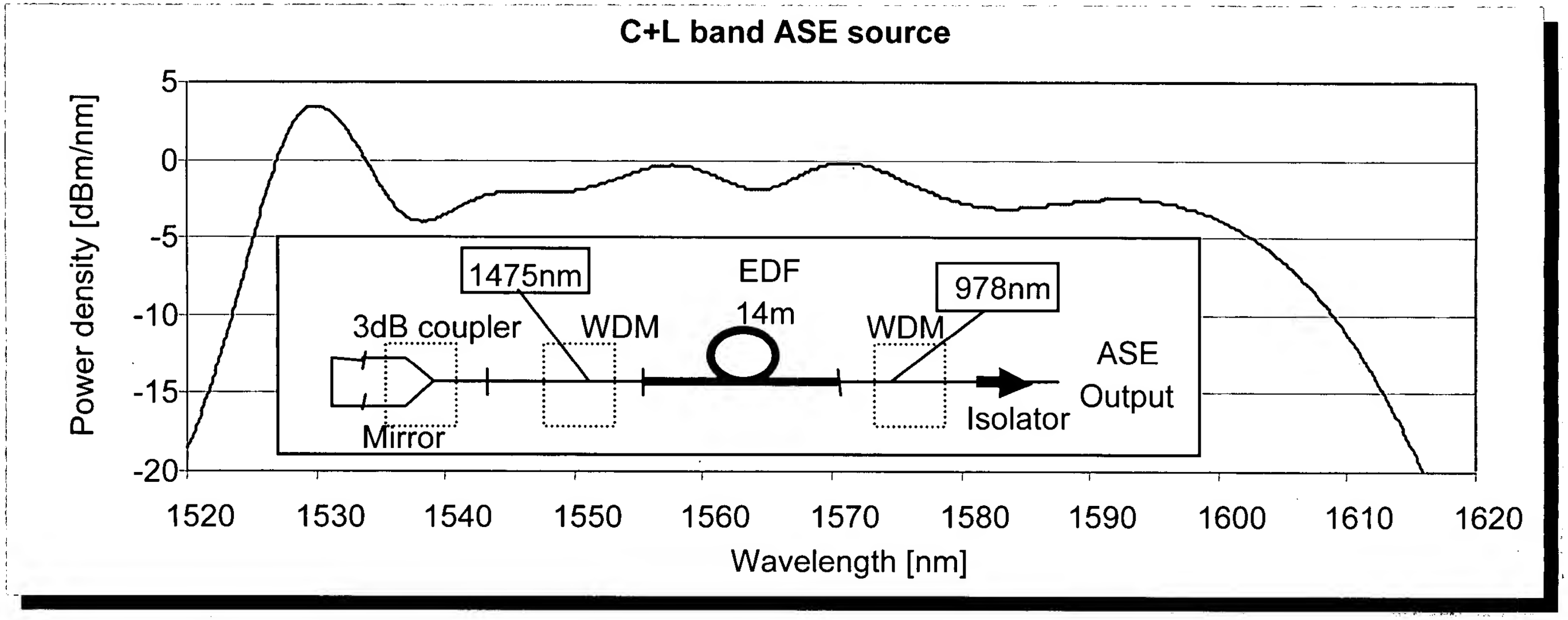
DND fibers: Improved efficiency L-band

- Absorption 30 dB/m @ 1530 nm
- Cut-off @ 1100 nm
- 22 m long fiber
- Saturating signal 0dBm @ 1580 nm
- Pump forward 100 mW @ 976.7 nm
- Pump backward 145 mW @ 1476 nm
- QCE 65%



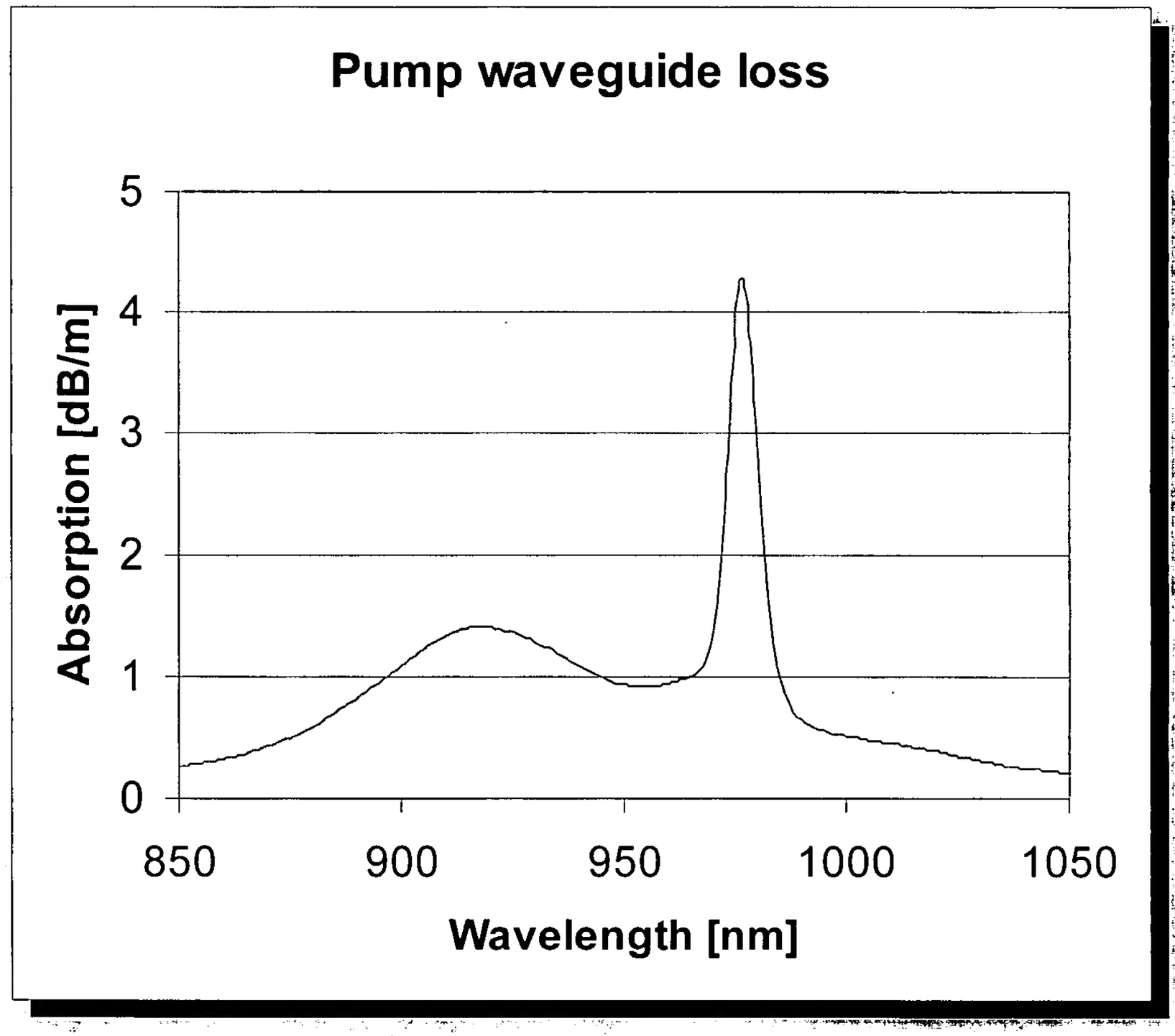
DND fibers: ASE source

- The broad band gain bandwidth results also broad ASE sources
- When the gain at C and L band are close enough it is possible to make C+L band ASE source using one active fiber



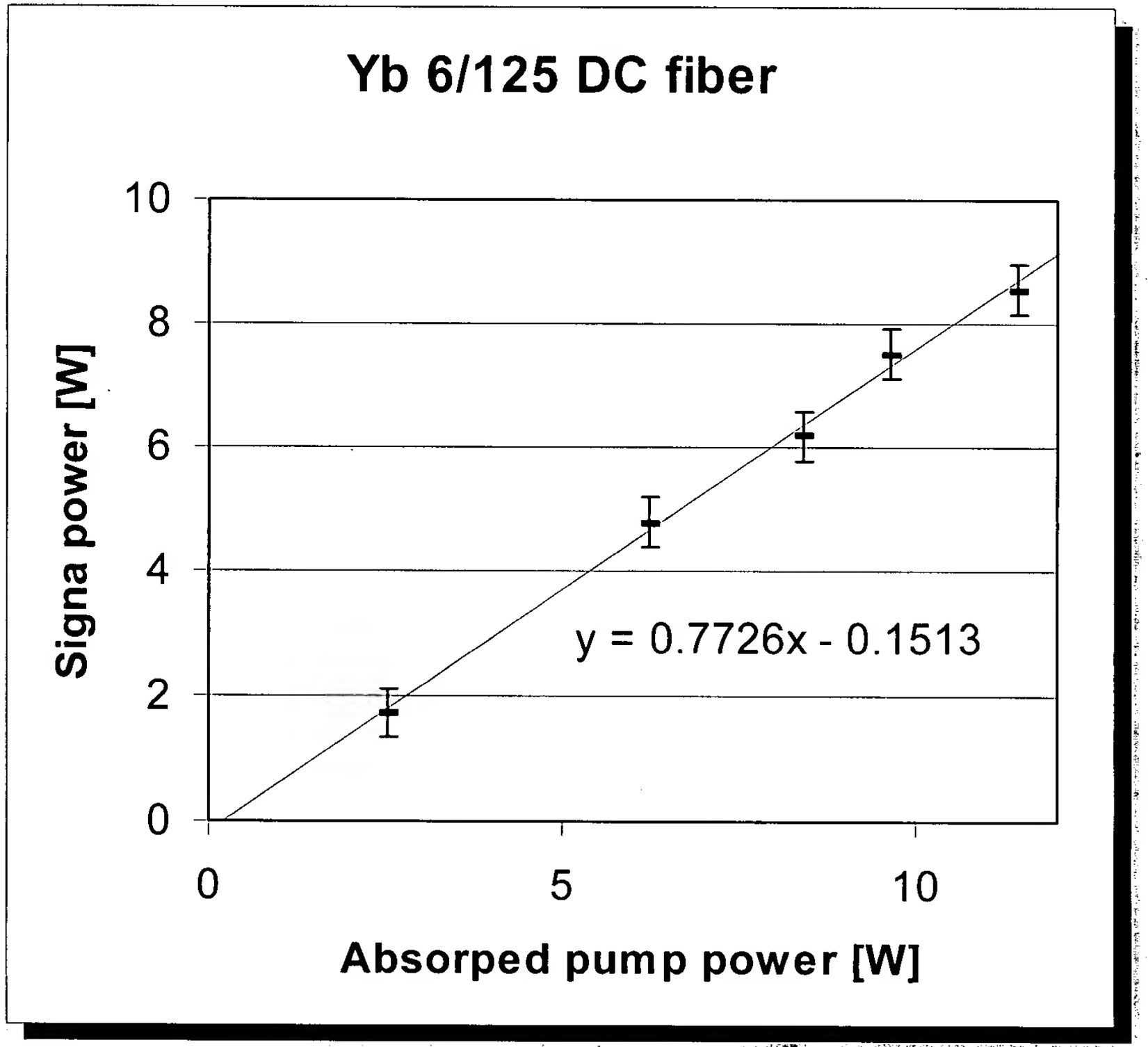
DND fibers: Yb doped fibers

- Core / Cladding ratio is 6/125
- Core absorption about 2000 dB/m
- Pump absorption 1.4 dB/m @ 920 nm



DND fibers: Yb DC fibers for lasers

- End pumping measurement
  - 10 m of Yb fiber
  - Core diameter 6 um
  - Cladding 125 um
  - Low n polymer cladding
  - Core absorption: 2300 dB/m @ 978 nm



Conclusion

Nanoparticle technology provides

- Possibility to use high and low vapor pressure materials simultaneously
- Possibility to produce uniform material both in nano- and macroscopic scale
- Independent selection of deposition process and preform geometry
- Scalability

To rare-earth doped fibers this means

- Higher concentrations, shorter fibers, less optical non-linearity and dispersion
- Better uniformity in doping and in spectral properties
  - Within fiber, both in lateral and longitudinal
  - From fiber to fiber
- Simpler preform glass work
- Wide range of core/cladding ratios (small to large)

Potential of nanoparticle technologies for next generation erbium-doped fibers

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Abstract: Nanoparticle technologies improve the doping processes. This results superior uniformity, higher erbium concentration and better control of refractive index profile. The nanoparticle technology will improve the economics and the quality of the erbium doped fiber.

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1. Introduction

While the long haul transmission market is slowly recovering from the depression the new applications for the erbium-doped fibers are emerging such as the amplifiers for the metro and the local area networks, amplifiers for the free space optical transmission systems, broad-band high power optical sources for sensing applications, and short pulse sources for eye safe range finding equipment.

Both the new and the old applications have at present tight cost frame. Thus the current requirements are, beside reasonable fiber pricing, also high conversion efficiency and guaranteed performance of the Er-fiber. E.g. the increase of the wavelength channel count, optical power levels, and the transmission speed result tighter tolerances to the polarization and optical non-linearity properties.

The nanoparticle techniques provide means to accurately control the erbium doping process. The rare earth environment can be engineered; the nanoparticle technology includes the possibility to co-dope the glass with versatile flexibility. This enables higher concentrations, better control on dopant uniformity, and consistent spectral characteristics. The higher concentration means shorter fiber and thus less optical non-linearity, less dispersion and less polarization mode dispersion.

The good doping control means also uniform and controlled refractive index profile, opening up the possibility to use different waveguiding effects and preventing the unwanted mode coupling.

2. Dissolving erbium into glass

In pure silica there are very few non-bridging oxygen atoms. The tetrahedron structure of the silica and the low number of non-bridging oxygen enables only low solubility of erbium ions, which have non-matching amount of charge for the coordination to the silica matrix [1]. The erbium inclusion to pure silica causes a distortion of the electronic charge cloud of the erbium ions, which leads to strong Stark splitting and to the narrowing of the bandwidth.

The use of alkali-metals or aluminium as co-dopants multiplies the amount of the non-bridging oxygen, and thus increases the erbium solubility. Because these co-dopants alter the glass structure, they also affect the Stark splitting and thus change the spectral characteristics of the erbium.

2.1. Concentration quenching

When the distance between two erbium ions becomes short they start to couple with each other. This results concentrations quenching, which is due to cooperative upconversions. The upconversion is a non-radiative energy transfer process due to electric multipolar interactions. In the starting point both of the ions are in the excited stage $^4I_{13/2}$. After the interaction the donating ion is transferred to ground state, $^4I_{15/2}$, and the acceptor ion is transferred to the $^4I_{9/2}$, from which it relaxes to the metastable state, $^4I_{13/2}$. The energy of the excited donor atom is lost to phonons in this process. The upconversion processes are divided into two categories; the homogeneous and the inhomogeneous. The homogeneous upconversion is a result of overall distribution of interionic distances in the glass network. In the inhomogeneous upconversion a portion of the erbium ions have formed clusters. The only method to limit the concentration quenching due to upconversion process is the control of the erbium ion distances.

3. Conventional rare-earth doping processes

The main challenge in manufacturing rare earth doped fibers has been the search for glass forming process, which can handle the low vapor pressure raw materials like rare-earth halides [2]. The organo-metallic sources have been tried also as gaseous rare earth source, unfortunately without any major success due to their high reactivity.

The liquid source methods have been successful, especially the solution doping technique [2]. In this process a porous layer of silica glass is produced on the inner side of a quartz tube. The tube is soaked into water containing Erbium salts, like $ErCl_3$. After drying the porous layer, the chloride with its crystalline water ($ErCl_3 \cdot 6(H_2O)$) is heated, and the erbium chlorine forms hydroxide ($Er(OH)_3$) and hydrochloric acids (HCl). When the temperature is further increased the oxides are formed and the extra water is released from the erbium hydroxide. Finally, the heat is high enough for the erbium oxide diffusion into silica glass and the sintering of the porous glass. There are some limitations with the solution doping process: the salts have a tendency to self-associate into chemical structures and thus form easily high local concentration variations into the glass. The porosity of the soot layer is difficult to control, and subsequently the dopant concentrations. The number of different layers is also limited.

4. Nanoparticle rare-earth doping technologies

The small size of the dopant particle improves both the microscopic and macroscopic uniformity when the aggregation is prevented. There are several factors that affect to the aggregation: the forces that keep the particle clusters together (e.g. ionic forces), the concentration of the nanoparticles, the time the particles are free to move and the speed of the particles. When producing homogeneous particles comprising from different elements, the particle forming conditions are important. The combination of high velocity and high temperature gradients improve the homogeneity.

Quite recently A. Le Sauze et al presented a new Nanoparticle Doping process where nanoparticles are synthesized in a separate process and then blended into a liquid. The nanoparticles are incorporated into the porous glass using the solution doping process. The experiments showed it is possible to incorporate erbium into GeO_2 – SiO_2 glass, which have low erbium solubility [3].

The Direct Nanoparticle Deposition (DND), developed by Liekki Oy, is based on the combustion of gaseous and atomized liquid raw materials in an atmospheric oxy-hydrogen flame [4]. The flexibility in raw material feeding gives the freedom of incorporating materials with very different vapor pressures. Thus it is possible to combine high-vapor pressure materials (like $SiCl_4$) and low vapor-pressure materials (like Er-salts). Feeding the precursor solution in the liquid phase directly to the reaction zone overcomes the conventional doping concentration limit. The glass is doped in-situ with the glass particle formation in such a way that the clustering tendency is low. Thus the DND process makes it possible to mix the index difference forming materials with other dopant materials already during the deposition of the glass particles, which improves the homogeneity of the glass composition prior to the sintering phase. Rapid quenching and a short residence time produce small particles with narrow size distribution. Typically the particle size can be adjusted between 10 and 100 nm.

One of the critical features of the DND process is the formation of micron-sized liquid droplets in the burner. At high production rates, the atomization needs to be situated as close to the point-of-use of the fine droplets as possible, otherwise the droplets tend to agglomerate to larger droplets. The formation of a nanoparticle from a micron droplet is a complicated process. Various parameters affect the formation process, e.g. the vapor pressure of the metals, temperature of the flame, gas velocities, droplet route through the flame and the Gibbs free energy of the raw materials. It is very tedious to study the different formation mechanisms experimentally. However, the qualitative results obtained from the particle size distribution measurement shows a single-peaked particle-size distribution, which indicates that the particles are formed through evaporation-condensation process.

5. Results with Direct Nanoparticle Deposition

In the DND preforms the radial variation of the doping concentration in the core is below 5 % [4]. The controllability of the local environment of the erbium ions is good enough so that the absorption spectrum shape does not depend on the doping concentration, Fig. 1.

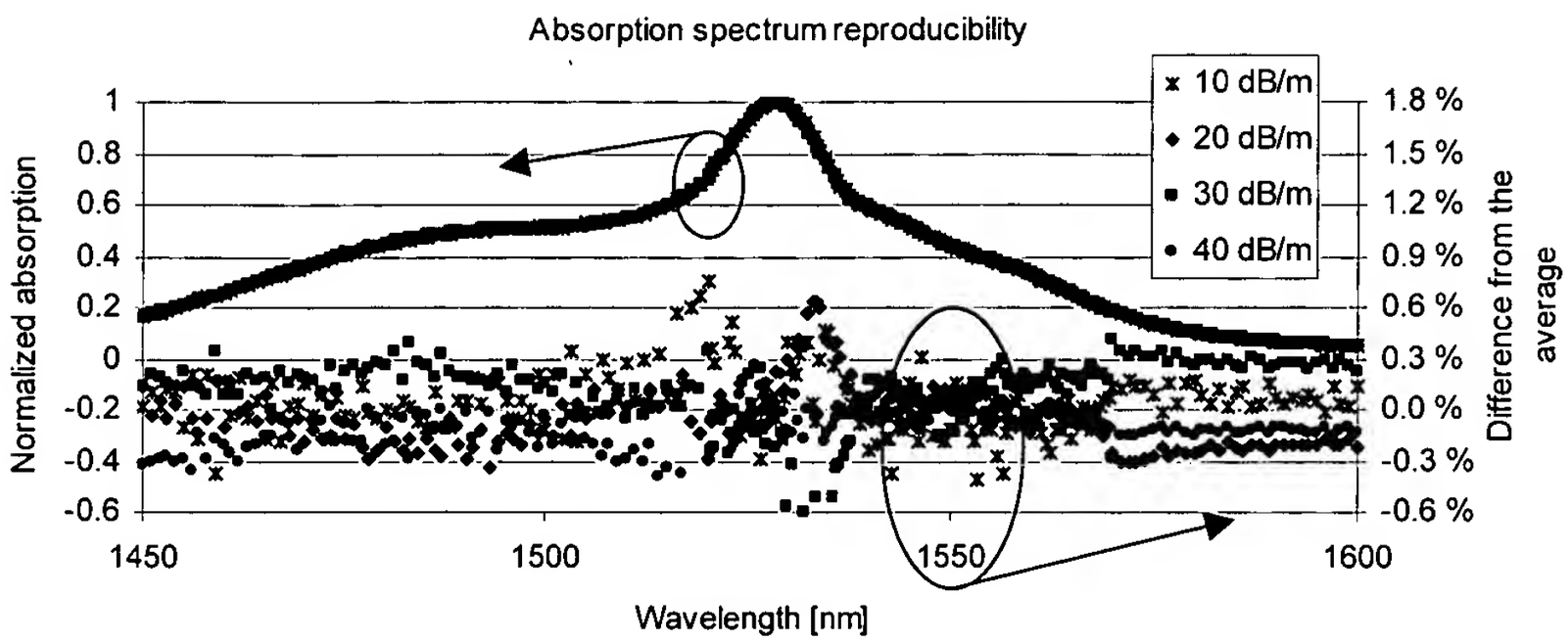

Fig 1. The normalized absorption spectrum of four different erbium doped fibers having peak absorptions of 10, 20, 30 and 40 dB/m. The possible variation of the spectrum shape is below the measurement accuracy.

The ability to control the local environment of the erbium ion also produces broad absorption and emission cross-sections, which can be utilized in L-band amplifiers [5], lasers [6] and ultra broadband ASE sources, Fig. 2.

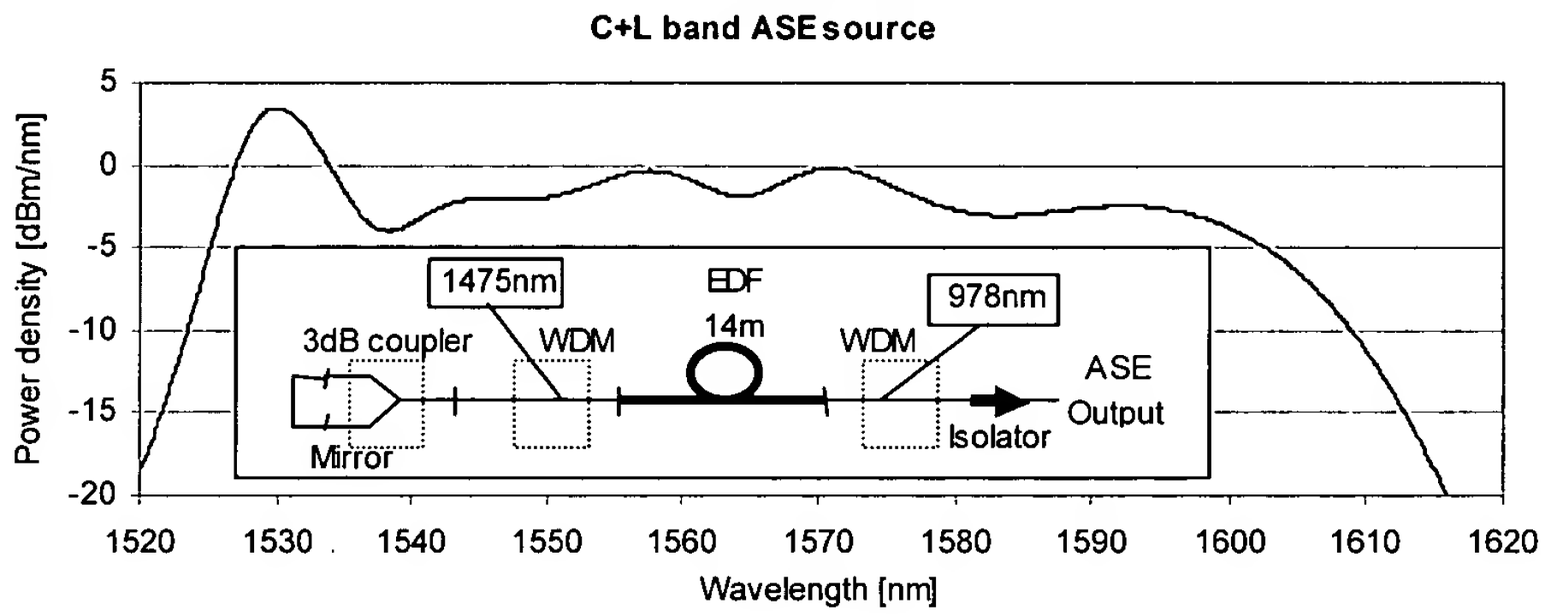

Fig 2. The C+L band ASE source can be built using one erbium doped fiber, when the difference of the gains at C- and L-band is not too large.

6. Conclusion

The nanoparticle technologies will improve the optical qualities of the erbium doped fiber further on. The improved control on doping level and uniformity, and the possibility to engineer the local environment of the erbium ion will have a clear technology push for the applications requiring better properties for handling high optical powers and fighting the optical non-linearity. Similarly, the better control on spectral properties will give an impact on the techno-economical puzzle of finding cost effective solutions for the amplification needs in the future.

7. References

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